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High-K Material Based Leaky-wave Antenna Design, Implementation, and Manufacture

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High-K Material Based Leaky-wave Antenna Design, Implementation, and Manufacture

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering

by

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2012
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GRADUATE SCHOOL

September 5, 2012

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Jiahui Wang ENTITLED High-K Material Based Leaky-wave Antenna Design, Implementation, and Manufacture BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

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ABSTRACT

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Leaky-wave antennas are a class of antennas which apply a traveling wave on a guiding structure as the main radiation mechanism. The properties of leaky-wave antennas are light weight, easy to fabricate, and readily integrated into conventional millimeter-wave systems. These features make leaky-wave antennas attractive. The most important characteristic is that the antenna can steer the beam direction through changing the operating frequency rather than switching the antenna itself. Variety types of leaky-wave antennas have been introduced and developed during the past 70 years. However, there is no existing leaky-wave antenna which can widely steer the beam scanning angle by changing smaller operating frequency. In this thesis, a portable and powerful leaky-wave antenna is designed, implemented, and demonstrated for scanning application. We change the guiding structure by applying a high dielectric constant material to produce a low-cost, small size, light weight, and high sensitivity leaky-wave antenna. The designed antenna can reach large scan angles with small frequency tuned. The unique features of such leaky-wave antenna are: (1) it is a light-weight, small-size, and portable antenna; (2) by slightly varying the operating frequency from 2.4 GHz to 2.7 GHz, 70 degree scanning angles can be achieved continuously; (3) it is an agile antenna; with 500 MHz operating frequency tuned, the direction of the beam can be easily changed; (4) it could be used as a low-cost phase array antenna.

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Introduction

1.1 Motivation

Leaky-wave antennas are a class of antennas which apply a traveling wave on a guiding structure as the main radiation mechanism [1][2][3]. The phase velocity is usually greater than the speed of light. Such antennas have been investigated in [4][5][6][7][8]. The theory to derive the dispersion properties of guiding structures has been thoroughly studied in [9][10][11][12]. The properties of leaky-wave antennas are light weight, easy to fabricate, and readily integrated into conventional millimeter-wave systems. These features make leaky-wave antennas attractive. The most important characteristic is that the antenna can steer the beam direction through changing the operating frequency rather than switching the antenna itself. Variety types of leaky-wave antennas have been introduced and developed during the past 70 years. Depending on the geometry and principle of the operation, the leaky-wave antenna could be designed either one-dimensional (1D) leaky-wave antenna or two-dimensional (2-D) leaky-wave antenna. Depending on the guiding structure, the leaky-wave antenna could be uniform, quasi-uniform, or periodic.

Most of the initial leaky-wave antennas were closed waveguide based. The structure is shown in Figure 1.1. Such antennas were hard to leak waveguide with low leakage per unit length [13] since the current lines in the closed waveguide

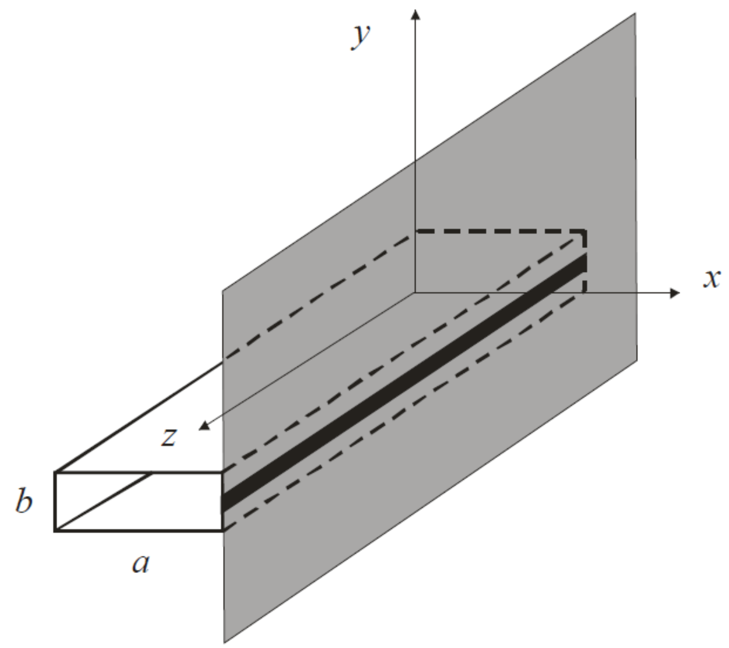


Figure 1.1: The First Known Leaky-wave Antenna with Slitted Rectangular Waveguide

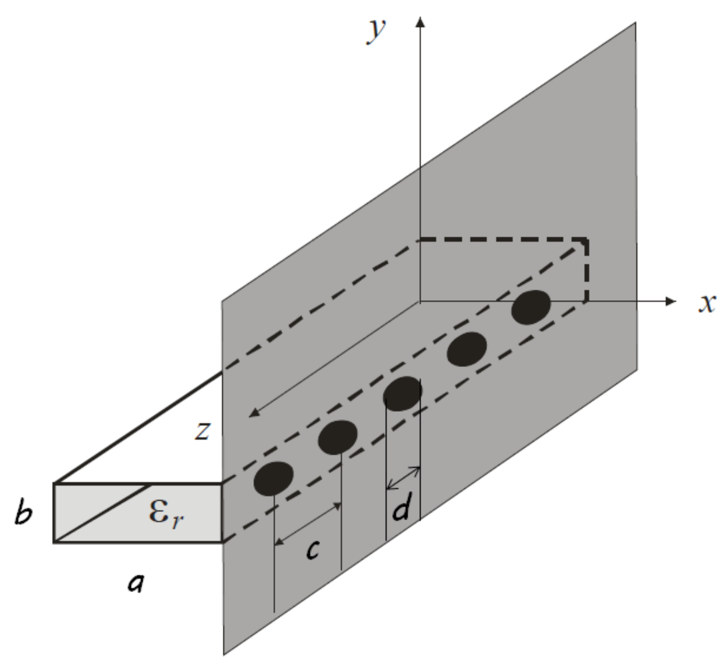


Figure 1.2: Example of 1-D Periodic Leaky-wave Antenna

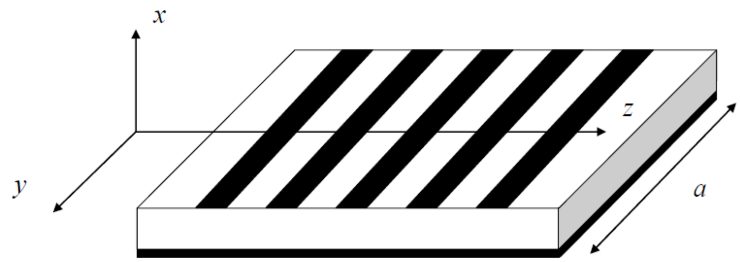


Figure 1.3: Leaky-wave Antenna with Closely-spaced Array of Metal Strips over a Ground Plane

were cut across by the slits. In [14], a “holey waveguide” structure was proposed, which used a series of closely spaced holes instead of a long uniform slit. Figure 1.2 shows its structure. By using a series of holes, the current lines won’t be cut where solves the problem in previous leaky-wave antenna. In Figure 1.2, if the waveguide is air-filled and the holes are spaced closely, it is called quasi-uniform leaky-wave antenna [3][15]. In [16], an open waveguide was applied. To radiate, a simple form of asymmetry was added to make asymmetrical trough waveguide antennas. Arrays of 1-D leaky-wave antennas were performed in [17]; and, 2-D leaky-wave antennas were developed in [18][19]. Other example such as the one shown in Figure 1.3 [3] was studied in [20], which consists of a closely-spaced array of metal strips over a ground plane. The transverse width of the structure is large relative to a wavelength, and is comparable to the length. The electric field is in the y direction and parallel to the strips. It can scan from 20° to 60° as the frequency changes from 7 GHz to 13 GHz. The nature of the leakage from higher modes on microstrip line with either open or covered tops has been well studied in [21]. In [22], a simple design of dual-beam leaky-wave antennas in microstrips is implemented. The range from 19° to 25° can be achieved between 5.56 GHz and 6.3 GHz. In [23], a half-width microstrip leaky-wave antenna is implemented, where presents beam scanning of 45 degrees for an 8 GHz design and 30 degrees for a 16

GHz antenna design.

Due to the attractiveness of leaky-wave antenna, more and more researchers design leaky-wave antennas for difference applications, such as for millimeter-wave applications. However, there is no existing leaky-wave antenna which can widely steer the beam scanning angle by changing smaller operating frequency. In this thesis, we change the guiding structure by applying a high dielectric constant material to produce a low-cost, small size, light weight, and high sensitivity leaky-wave antenna. By changing frequency from 2.4 GHz to 2.7 GHz, such antenna can continuously scan 70 degrees. By lowering the operating frequency from millimeter-wave band, such antenna can be widely used in other applications.

1.2 Introduction to Leaky-wave Antenna

The earliest example of leaky-wave antenna is a rectangular waveguide with a continuous slit cut along its length, which is shown in Figure 1.4 [24]. Leakage occurs long the length of the slit in the waveguide structure; hence, the antenna's effective aperture is the whole length. However, if the leakage rate is too high to make the power totally leaked before it reaches the end of the slit, the antenna's effective aperture is less than the whole length of the waveguide. The leakage causes the leaky waveguide a complex propagation waves with a phase constant β and a leakage constant α. Leakage per unit length is large if α is large, and it is small if α is small. Therefore, a large α means the leakage per unit length is large so that the effective aperture of the antenna is short. It causes a large beamwidth of the radiated beam, and vise versa.

On the other hand, the main beam direction of the leaky wave antenna can be easily scanned. The change of frequency makes the phase constant β change so that the beam direction changes. Hence, by varying the frequency, the leaky-

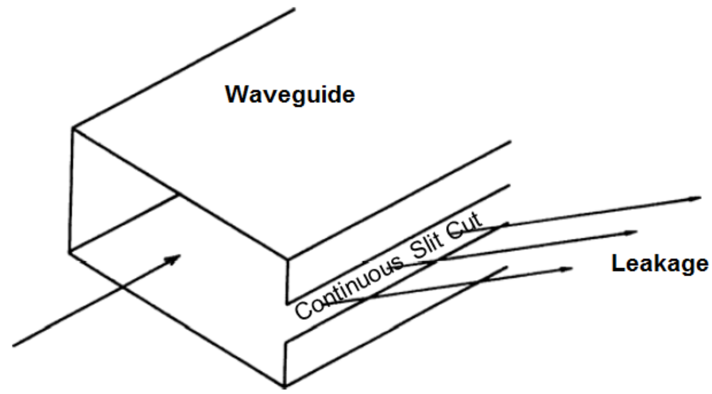


Figure 1.4: Leaky-wave Antenna Example

wave antenna is scanned. It is also other attractiveness of the leaky-wave antenna. The main beam angle θ, which is measured from broadside, is defined by the well-known expression as:

$$\sin\theta = \frac{\lambda_0}{\lambda_g} - m\frac{\lambda_0}{d} \tag{1.1}$$

where

d is perturbation spacing;

λ_0 is wavelength in vacuum;

λ_g is guided wavelength inside the dielectric rod;

m is integer and usually equals to unity.

By changing the operating frequency, scanning can be achieved, and the free-space wavelength λ_0 as well as the guided wavelength λ_g are changed.

1.3 Thesis Contribution

In this thesis, a new guiding structure is built with high dielectric constant material, PZT. A low cost, small size, high sensitivity leaky-wave antenna is designed, implemented, and demonstration. This experimental testbed can be easily and widely used for related research. The contribution of the thesis could be summarized as:

1. Build a light-weight, small-size, agile, and portable leaky-wave antenna via new guiding structure;
2. Achieve the goal of using narrow frequency range to reach large angle sweep;
3. Find a way to reduce the cut-off frequency of the leaky-wave guide antenna;
4. Find a way to reduce the length of the high leaky wave guide antenna;
5. Use the designed leaky-wave antenna as a low-cost phase array antenna.

1.4 Thesis Organization

There are four chapters in this thesis. Chapter 1 introduces the motivation of the project and reviews the history of leaky-wave antennas; Chapter 2 analyzes the leaky-wave antenna design with simulation results; Chapter 3 implements and demonstrates such antenna; Chapter 4 gives the conclusion and future work.

EMPro-based Leaky-wave Antenna Design

2.1 Overview of Leaky-wave Antenna

Leaky-wave antenna uses traveling wave on a guiding structure to radiate by leaking power all along its length. It is designed either to radiate in certain direction or to scan over a range of angles. The properties of leaky-wave antennas are light weight, easy to fabricate, and readily integrated into conventional millimeter-wave systems. On the other hand, the main beam direction of the leaky wave antenna can be easily scanned by changing the frequency. These features make leaky-wave antennas attractive.

Leaky-wave antenna can be classified as either uniform leaky-wave antenna or periodic leaky-wave antenna based on the geometry of the guiding structure is uniform or periodic modulation along its length, respectively.

2.1.1 Uniform Leaky-wave Antenna

Uniform leaky-wave antenna is uniform along the length of the guiding structure, which has a small taper along its length so that the sidelobe level could be improved and controlled. Uniform leaky-wave antenna supports a fast wave so that it leaks power all along the waveguide length whenever the structure is open.

The physical structure of such leaky-wave antenna has a leaky waveguide with a length L along where the leakage occurs. The propagation characteristics of the leaky mode in the longitudinal (z) direction are given by phase constant β, and leakage constant α which is the measurement of the power leakage per unit length. Then, the length L forms the aperture of the line-source antenna, and the amplitude and phase of the traveling wave along the aperture are determined by the values of α and β as a function of z. Leakage constant α and phase constant β do not change with z if the leaky waveguide is absolutely uniform along the length. Meanwhile, the aperture distribution has an exponential amplitude variation and a constant phase [2].

The beam direction and the beamwidth of uniform leaky-wave antenna are defined as:

$$\sin\theta_m \approx \frac{\beta}{k_0} \tag{2.1}$$

$$\Delta\theta \approx \frac{1}{(L/\lambda_0)\cos\theta_m} \tag{2.2}$$

where

- θ_m is the maximum beam angle (in radians);
- β is phase constant;
- k_0 is the free-space wave number, which is equal to $2\pi/\lambda_0$;
- L is the length of leaky-wave antenna;
- $\Delta\theta$ is the leaky-wave antenna beamwidth, in radians.

The beamwidth $\Delta\theta$ is determined primarily by the antenna length L, but it is also influenced by the aperture field amplitude distribution. It is narrowest for a constant aperture field and wider for sharply peaked distribution [2]. Equation 2.2 is the medium value. When the antenna length L is chosen and if we want 90% power is radiated, [2] finds

$$\frac{L}{\lambda_0} \approx \frac{0.18}{\alpha/k_0} \tag{2.3}$$

The relationship between the power remaining in the leaky mode and the input power is:

$$\frac{P(L)}{P(0)} = \exp(-2\alpha L) = \exp\left[-4\pi(\alpha/k_0)(L/\lambda_0)\right] \tag{2.4}$$

2.1.2 Periodic Leaky-wave Antenna

Periodic leaky-wave antenna uses periodic modulation of the guiding structure. The periodic itself is uniform long the length of structure. The periodicity produces the leakage. Figure 2.1 shows a typical example of the periodic leaky-wave antenna [2], which is a dielectric rectangular rod on which a periodic array of metal strips is placed. Before metal strips are added, the frequency which is larger than the cutoff frequency is chosen so that $\beta > k_0$, which is purely bound. Then, the periodic array of strips are added to make it periodicity which could introduce an infinity of space harmonics, where each characterized by space constant β_n and related to each other by [2]:

$$\beta_n d = \beta_0 d + 2n\pi \tag{2.5}$$

where d is the period; β_0 is the fundamental space harmonics, and simply the original β of the dominant mode of the uniform dielectric waveguide; β_n can be any value to make the space harmonics be either forward or backward in nature, and

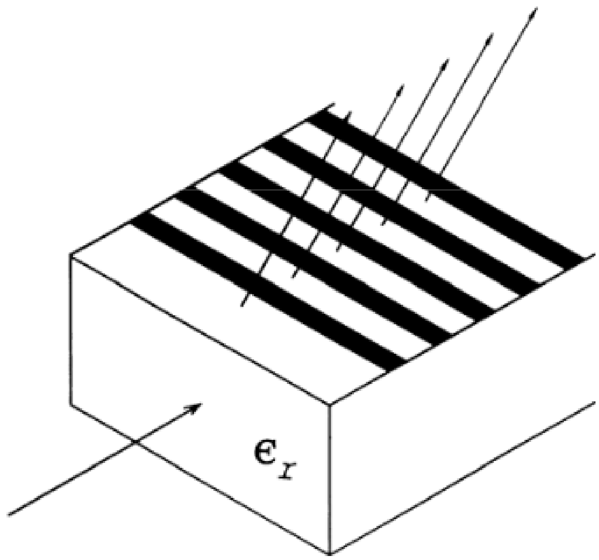


Figure 2.1: A Periodic Leaky-wave Antenna

either fast or slow. Since we desire the antenna to radiate only a single beam, the structure is designed to make only the first space harmonic, where $n = -1$, fast. This is also the main difference relates to the periodic leaky-wave antenna.

Therefore, through replacing β by β_{-1} in Equation 2.2, the beam direction of periodic leaky-wave antenna can be defined as:

$$\sin\theta_m \approx \frac{\beta_{-1}}{k_0} \tag{2.6}$$

where

$$\beta_{-1} = \beta_0 - \frac{2\pi}{d} \tag{2.7}$$

By substituting Equation 2.7 into Equation 2.6, we get

$$\sin\theta_m \approx \frac{\beta_0}{k_0} - \frac{2\pi}{k_0 d} = \frac{\lambda_0}{\lambda_{g0}} - \frac{\lambda_0}{d} \tag{2.8}$$

Therefore, depending on how λ_0/d compares with λ_0/λ_{g0} (or β_0/k_0), the beam could point to the direction either in backward quadrant or in forward quadrant.

Again, the beamwidth is

$$\Delta\theta \approx \frac{1}{(L/\lambda_0)\cos\theta_m} \tag{2.9}$$

and, Equation 2.3 and Equation 2.4 can also be applied to periodic leaky-wave antenna with β_{-1} substituting β.

2.2 EMPro-based Simulation of Leaky-wave Antenna Design

Leaky-wave antenna has been reviewed and studied in Section 2.1. To meet our requirements to build a low-cost, small size, light weight, and high sensitivity leaky-wave antenna, which can achieve large scanning angles continuously by slightly varying the operating frequency, we first change building structure and build a novel guiding structure using high dielectric constant material. However, to build such antenna, besides the knowledge of dielectric constant of the antenna, we also need to know how the length of the antenna, the size of the slots, and the distance between every adjacent slots effect the design.

2.2.1 EMPro Simulation Tool

Electromagnetic Professional (EMPro) [25] is a three-dimensional full wave electromagnetic (EM) solver. It is Agilent EEsof EDA's EM simulation software. EMPro EM simulation software features a modern design, simulation and analysis environment, high capacity simulation technologies and integration with the industrys leading RF and microwave circuit design environment, Advanced Design System (ADS) for fast and efficient RF and microwave circuit design [25]. It has two methods: Finite-Difference Time-Domain Method (FDTD) and Finite Element Method (FEM). Because FDTD cannot simulate waveguide structure, and cannot give the visual wavelength, we use FEM to simulate the leaky waveguide antenna in this design.

2.2.2 Simulation Structure

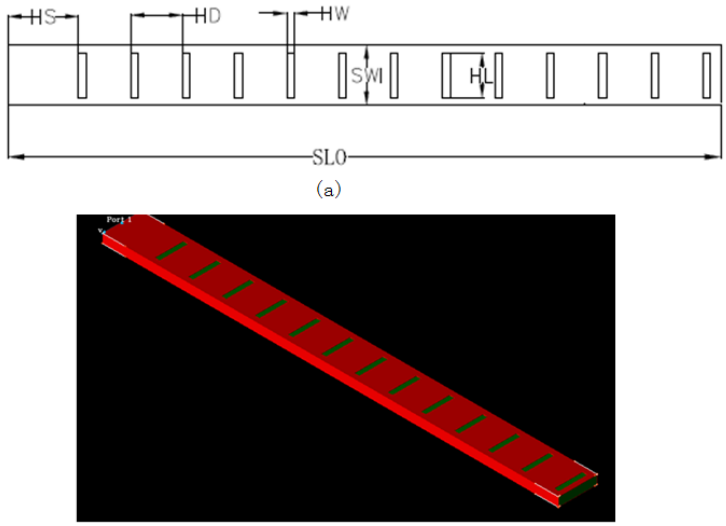
The simulation structure is illustrated in Figure 2.2. The red part in Figure 2.2(a) is copper with 0.1 mm thickness. The green bars is high dielectric constant material. Based on lots of simulation results, the size of the design antenna is chosen as:

the length of the antenna $SL0$	96 mm
the width of the antenna $SW1$	8 mm
the length of the slot HL	6 mm
the width of the slot HW	1 mm
the distance between every two slots HD	7 mm
the distance between port1 and the first slot HS	10 mm

2.2.3 Impact of Slot Width

The slot width is an important parameter of leaky waveguide antenna. The width cannot be very small because I will use milling machine to cut the slots of antenna; the blade of milling machine is at least 1 mm. However, the width of the slot cannot be very large. If the it is too wide relative to the wavelength in the waveguide, the slots cannot leak waves with specific phase difference. Thus, the leaky waves cannot interfere in the far-field.

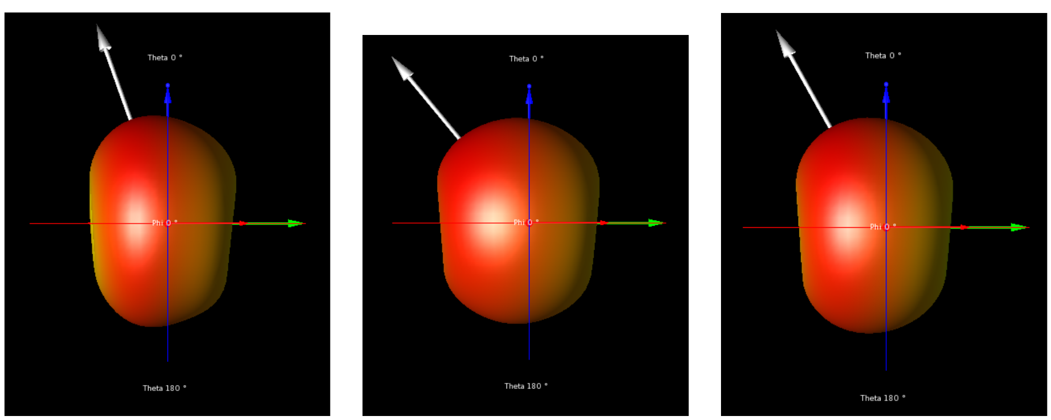
Figure 2.3 show the main beam direction when dielectric constant is $k = 137$, and the width of slot is $HW = 4mm$. When the RF frequency increase from 3.7



(a)

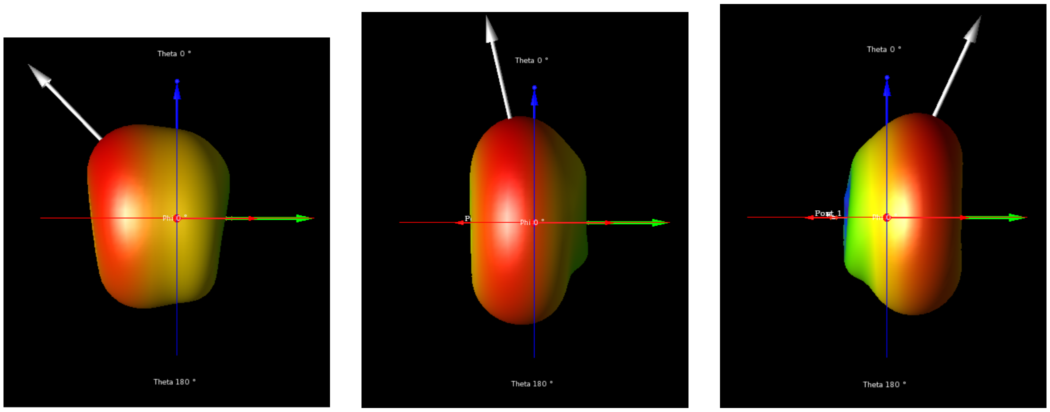
(b)

Figure 2.2: Simulation Structure



(a) (b) (c)

Figure 2.3: Dielectric Constant $k = 137$, Width of the Slot $HW = 4mm$ (a) Frequency $f_c = 3.7GHz$; (b) Frequency $f_c = 4GHz$; (c) Frequency $f_c = 4.2GHz$



(a) (b) (c)

Figure 2.4: Dielectric Constant $k = 137$, Width of the Slot $HW = 1mm$ (a) Frequency $f_c = 3.7GHz$; (b) Frequency $f_c = 4GHz$; (c) Frequency $f_c = 4.2GHz$

GHz to 4.2 GHz, no continuously changed main beam can be found.

However, we decrease the slot's width from 4 mm to 1 mm. The main beam directions for $f_c = 3.7GHz$, $f_c = 4GHz$, and $f_c = 4.2GHz$ are shown in Figure 2.4(a) , Figure 2.4(b), and Figure 2.4(c), respectively.

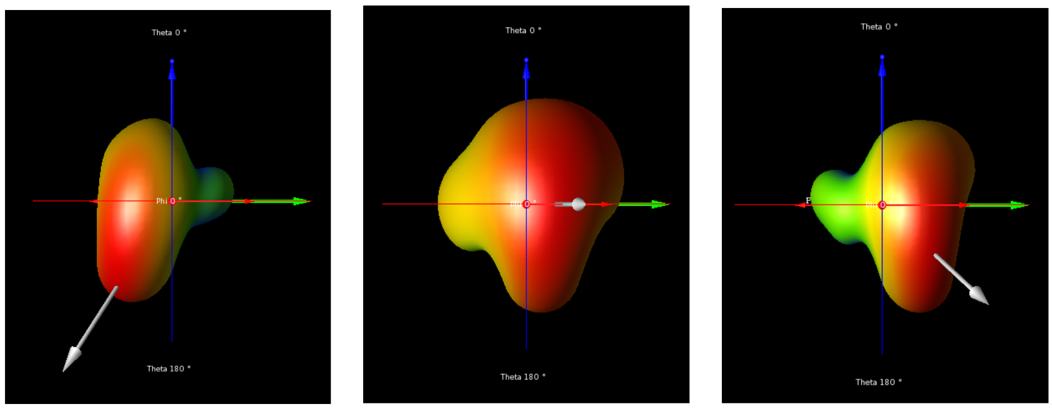
Obviously, when width of the slot is 1 mm, with tuning frequency, the main beam direction can be continuously changed. Therefore, the width of the slots cannot be too wide in our design. We set the width of the slots at 1 mm.

2.2.4 Impact of Slot Length

We also need to carefully choose the length of the slots. From lots of simulation, we find that a good beam we can be found when the length of the slots is 6 mm. However, what happens if the length of the slots is small?

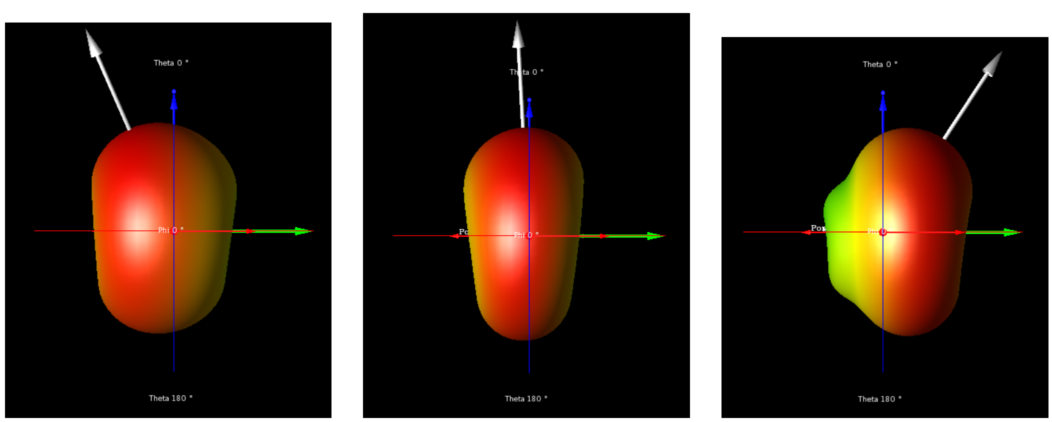
Figure 2.5(a) through Figure 2.5(c) illustrate the main beam directions with dielectric constant $k = 137$, and the length of the slots $HL = 2mm$ when the RF frequency is changed. Due to the short length of the slots, no main beam is found in the top quadrature and the angle changes randomly.

However, we increase the slot's length from 2 mm to 6 mm. The main beam



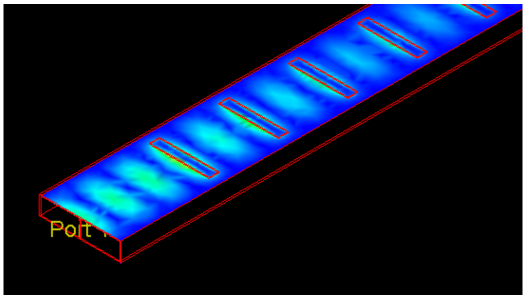
(a) (b) (c)

Figure 2.5: Dielectric Constant $k = 137$, Length of the Slot $HL = 2mm$ (a) Frequency $f_c = 2.45GHz$; (b) Frequency $f_c = 2.6GHz$; (c) Frequency $f_c = 2.65GHz$

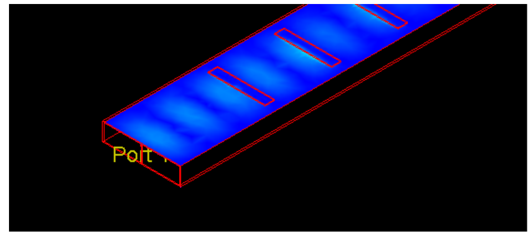


(a) (b) (c)

Figure 2.6: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$ (a) Frequency $f_c = 2.45GHz$; (b) Frequency $f_c = 2.6GHz$; (c) Frequency $f_c = 2.65GHz$



(a)



(b)

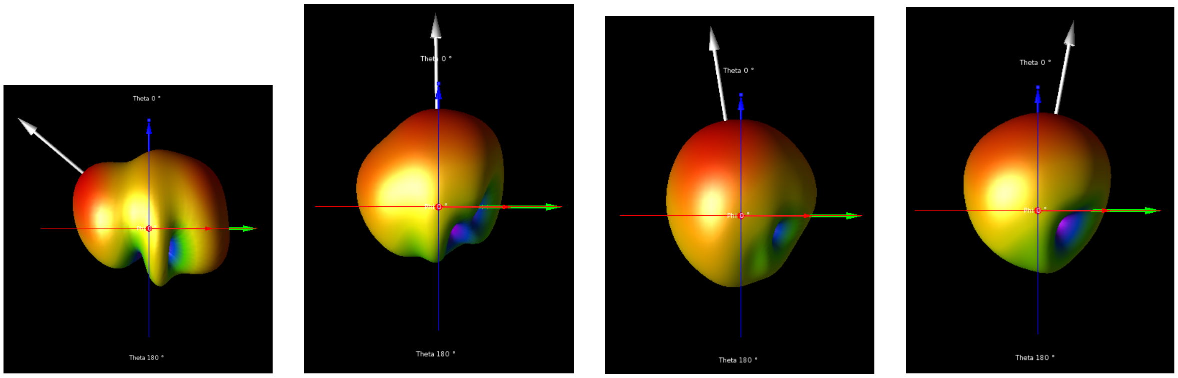
Figure 2.7: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$, Width of the Slot $HW = 1mm$, Slots Distance $HD = 7mm$ (a) Frequency $f_c = 2.6GHz$; Frequency $f_c = 2.4GHz$

directions for $f_c = 2.45GHz$, $f_c = 2.6GHz$, and $f_c = 2.65GHz$ are shown in Figure 2.6(a), Figure 2.6(b), and Figure 2.6(c), respectively. Obviously, when the length of the slots is 6 mm, with tuning frequency, the main beam direction can be continuously changed. Based on lots of simulation results, we find that a good beam we can be found when the length of the slots is 6 mm and width is 1 mm.

2.2.5 Impact of the Distance between the Adjacent Slots

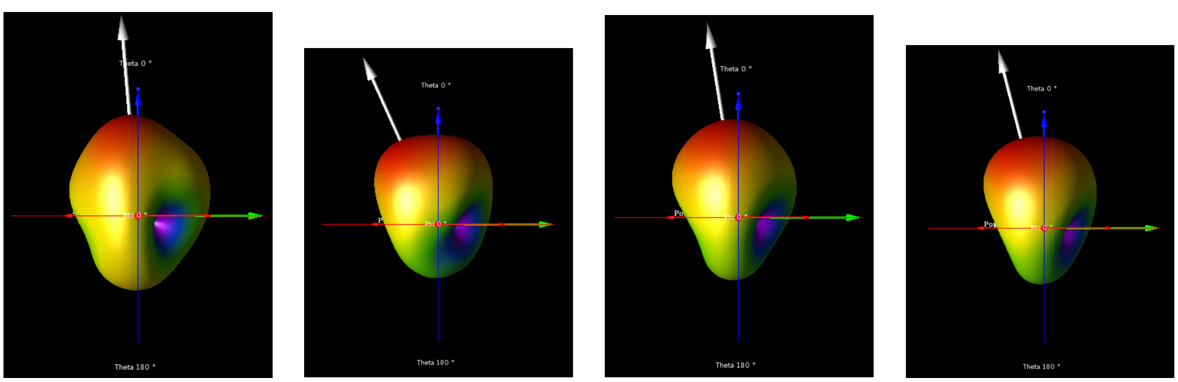
The distance between the adjacent slots should match the wavelength in the waveguide. The distance between adjacent slots in both Figure 2.7(a) and Figure 2.7(b) is 7 mm, which is equal to the wavelength in the waveguide. In Figure 2.7(a), the distance is equal to the wavelength in the waveguide so that the waves with the same phases achieve the slots at the same time. The waves with the same phases radiate to the free space. The main beam is vertical to the waveguide.

Then, the frequency is slightly decreased to 2.4 GHz, which means the wavelength in the waveguide becomes slightly longer. In Figure 2.7(b), we can see the first peak of wave does not reach the first slot; however, the second already reach the second slot. Thus, every leaky wave has phase difference which causes the main beam direction changed.



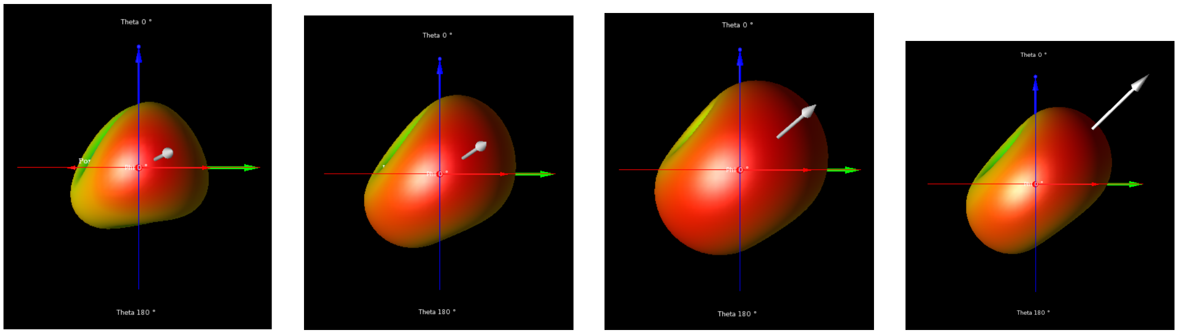
(a) (b) (c) (d)

Figure 2.8: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$, Width of the Slot $HW = 1mm$, Slots Distance $HD = 9mm$ (a) Frequency $f_c = 2.4GHz$; (b) Frequency $f_c = 2.5GHz$; (c) Frequency $f_c = 2.6GHz$; (d) Frequency $f_c = 2.7GHz$



(a) (b) (c) (d)

Figure 2.9: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$, Width of the Slot $HW = 1mm$, Slots Distance $HD = 5mm$ (a) Frequency $f_c = 2.4GHz$; (b) Frequency $f_c = 2.5GHz$; (c) Frequency $f_c = 2.6GHz$; (d) Frequency $f_c = 2.7GHz$



(a) (b) (c) (d)

Figure 2.10: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$, Width of the Slot $HW = 1mm$, Slots Distance $HD = 7mm$, Antenna Length $SL0 = 24mm$ (a) Frequency $f_c = 2.4GHz$; (b) Frequency $f_c = 2.5GHz$; (c) Frequency $f_c = 2.6GHz$; (d) Frequency $f_c = 2.7GHz$

If the slot distance is increased to 9 mm. Figure 2.8(a) through Figure 2.8(d) show the change of the main beam direction. However, no continuous change of the main beam direction is found.

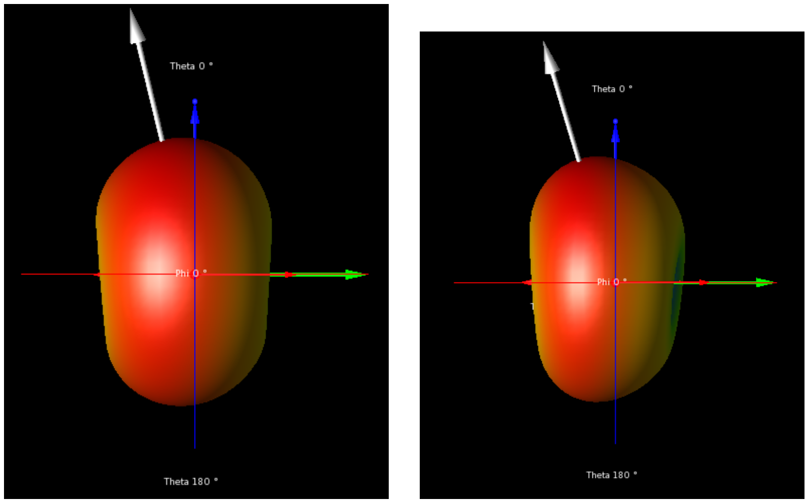
If the slot distance is decreased to 5 mm. Figure 2.9(a) through Figure 2.9(d) show the change of the main beam direction. Again, no continuous change of the main beam direction is found.

Hence, based on the simulation, the design with slot's size with 1mm width and 6 mm length, and 7 mm the distance of the adjacent slots give the best performance.

2.2.6 Impact of the Antenna Length

The length of the leaky waveguide should be bigger than 10 wavelengths in the waveguide. If it is shorter than 10 wavelengths, the most power will leak from the end of the antenna. This phenomenon could be observed from Figure 2.10(a) to Figure 2.10(d). These figures also show that the main beam direction does not change when the frequency is changed.

Therefore, for the design, 96 mm is chosen as the length of the antenna. The



(a) (b)

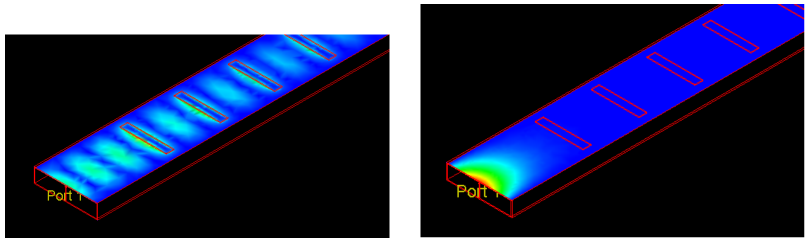
Figure 2.11: Dielectric Constant $k = 137$, Length of the Slot $HL = 6mm$, Width of the Slot $HW = 1mm$, Slots Distance $HD = 7mm$, and Frequency $f_c = 2.55GHz$ (a) Antenna Length $SL0 = 96mm$; (b) Antenna Length $SL0 = 200mm$

antenna could be made longer; however, the beam shape radiated by the longer size of the antenna, which is shown in Figure 2.11(a), is almost the same as the one radiated by 96 mm one, which is shown in Figure 2.11(b).

2.2.7 Impact of Dielectric Constant

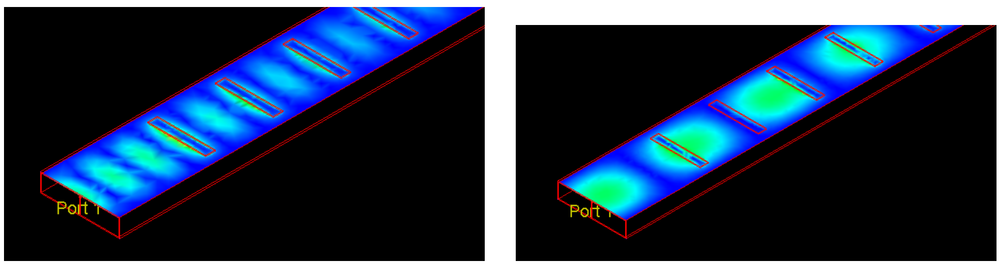
Based on the previous simulation results, we choose the antenna size with length $96mm$, width $8mm$, 13 slots with $6mm$ length and $1mm$ width, and $7mm$ distance between every adjacent two slots. In this section, let's see how dielectric constant can effect the performance.

We first set dielectric constant at 337. Figure 2.12(a) is the E-field plot and shows that the traveling wave centered at 2.6 GHz goes from port 1 to the end of the antenna. However, when set dielectric constant to 1, the same traveling wave cannot go through the waveguide and there is no radiation of leaky wave on the side of the slots; which is shown in Figure 2.12(b). Hence, to make the traveling wave leaked from the slots, we can either use low dielectric constant waveguide



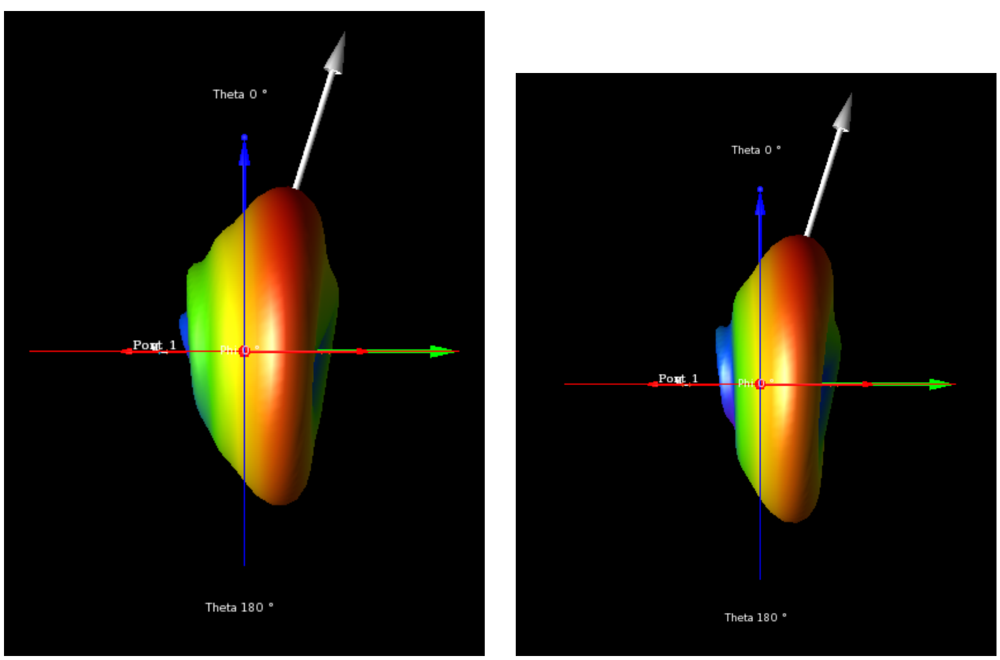
(a) (b)

Figure 2.12: E-field Plot when (a) $k = 337$ and $f_c = 2.6GHz$; (b) $k = 1$ and $f_c = 2.6GHz$



(a) (b)

Figure 2.13: (a) High Dielectric Constant Produces Low Wavelength of Waveguide; (b) Low Dielectric Constant Produces High Wavelength of Waveguide



(a) (b)

Figure 2.14: (a) $f_c = 4.2GHz$ and $k = 128$; (b) $f_c = 3.85GHz$ and $k = 152$

with high speed of traveling wave or use high dielectric constant waveguide with low speed of traveling wave.

On the other hand, dielectric constant can also effect the wavelength of the waveguide. Figure 2.13(a) is the E-field plot when $k = 337$, and Figure 2.13(b) is the E-field plot when $k = 100$. Hence, we can conclude that low dielectric constant produces high wavelength of waveguide, and high dielectric constant produces low wavelength of waveguide.

Therefore, the angle radiate pattern which is obtained at higher frequency can be also got by using the higher dielectric at low frequencies. Figure 2.14(a) shows the radiation pattern when $k = 128$, and $f_c = 4.2G$. Figure 2.14(b) shows that the similar pattern can be got when $k = 152$, and $f_c = 3.85GHz$.

2.2.8 Comparison among Different Dielectric Constant

Figure 2.15 illustrate the comparison among different dielectric constant. It is easy to tell that with high dielectric constant material, the operating frequency could be much lower; meanwhile, the large sweep angles could be achieved with small frequency tuned. The simulation results confirm our design. In next Section, we will manufacture the antenna and further validate the design by implementation and demonstration.

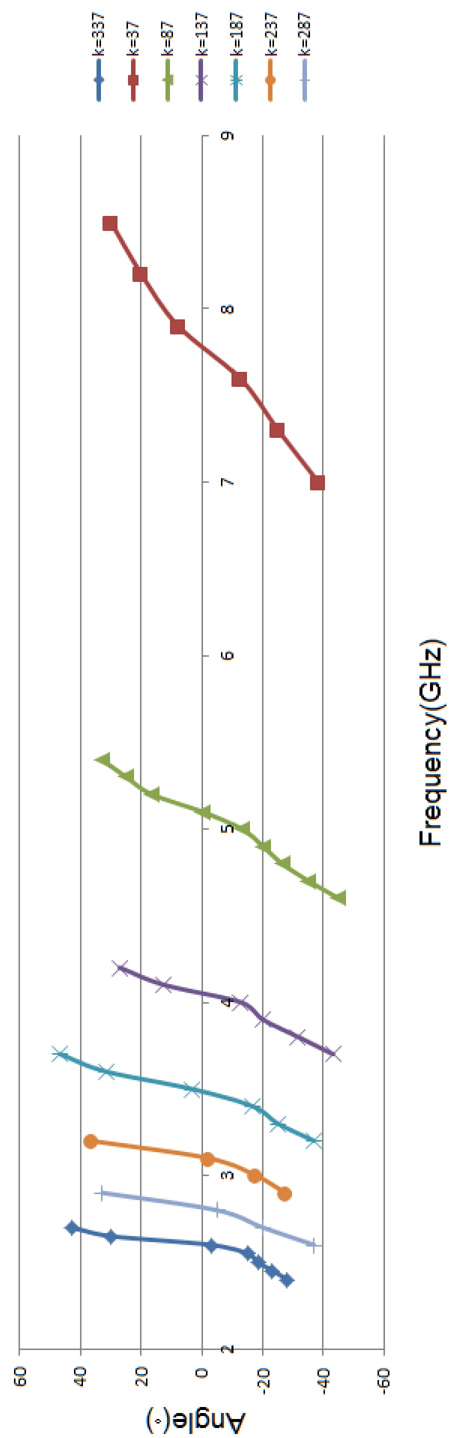


Figure 2.15: Comparison among Different Dielectric Constant

Implementation, Manufacture, and Demonstration of Leaky-wave Antenna

3.1 Implementation and Manufacture

In this Chapter, we will discuss the materials and the tools we use for building the testbed. After showing how we implement and produce such proposed antenna, we will present the demonstration results to validate our design.

3.1.1 Dielectric Constant with PZT

To increase the dielectric constant, Lead Zirconate Titanate (PZT) is applied. It is a ceramic perovskite material which shows a significant piezoelectric effect. This material has been widely used in electroceramics applications. The dielectric constant of PZT can range from 300 to 3850 depending on orientation and doping [26]. In this testbed, we choose the PZT with 1900 dielectric constant.

To change the dielectric constant of the antenna, we put PZT with 1900 dielectric constant on the top of a double-side copper printed circuit board (PCB),

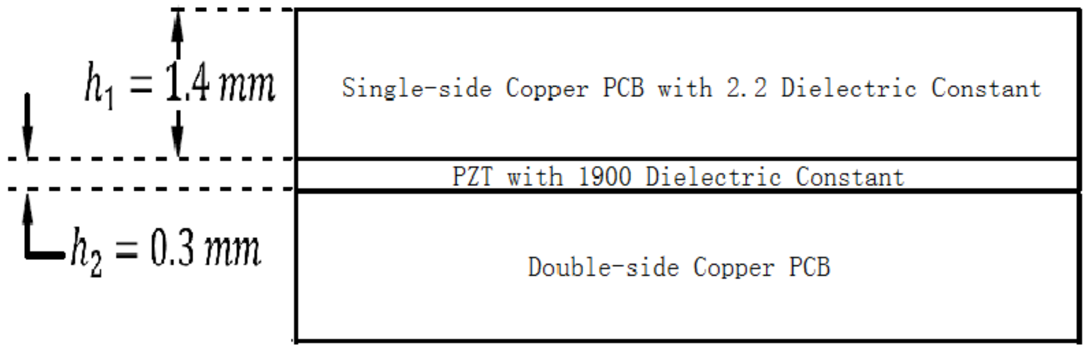


Figure 3.1: Longitudinal View of Leaky-wave Antenna

then we cover the PZT with a single-side copper PCB; where PCB is used to mechanically support and electrically connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive substrate [27]. The longitudinal view of the leaky-wave antenna is shown in Figure 3.1. The dielectric constant of the upper PCB is 2.2 with thickness of 1.4 mm and width of 8 mm. The length of the antenna is 96 mm. The thickness of PZT is 0.3 mm, and width of it is 8 mm. Hence, the dielectric constant of the antenna can be calculated as:

$$\begin{aligned} \epsilon &= \frac{\epsilon_1 \times h_1 + \epsilon_2 \times h_2}{h_1 + h_2} \\ &= \frac{2.2 \times 1.4 + 1900 \times 0.3}{1.4 + 0.3} \\ &= 337 \end{aligned}$$

Obviously, by using this design, we can match the simulation conditions with the one with 337 dielectric constant case. In Section 3.2, the demonstration results are provided which can validate the design which we have discussed in Chapter 2.

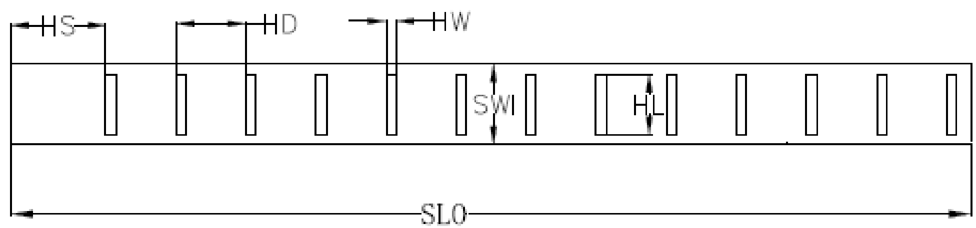


Figure 3.2: Size of the Designed Leaky-wave Antenna

3.1.2 Antenna Production

The top view of the antenna is shown in Figure 3.2. The length of the antenna $SL0 = 96mm$, and the width of it is $SW1 = 8mm$. There are 13 slots which are perpendicular to the x axis on the top copper of PCB. The width and the length of the slots are $HW = 1mm$ and $HL = 6mm$, respectively. The distance between the edge of PCB and the first slot is $HS = 10mm$. The distance between the centers of adjacent slots is $HD = 7mm$. The slots on the PCB can cut off the current.

The design flow of such antenna is shown in Figure 3.3. The antenna layout is drawn using AutoCAD. Then, AutoCAD will transfer the layout to Milling Machine to produce PCB with such requirements. After soldering the SMA connector on the antenna, we attach it onto a stick to make it fixed well. During the measurement, the antenna is not moved, but the receiver horn antenna is. The details will be discussed in Section 3.2 and you will see how beam direction is changed according to changed frequency.

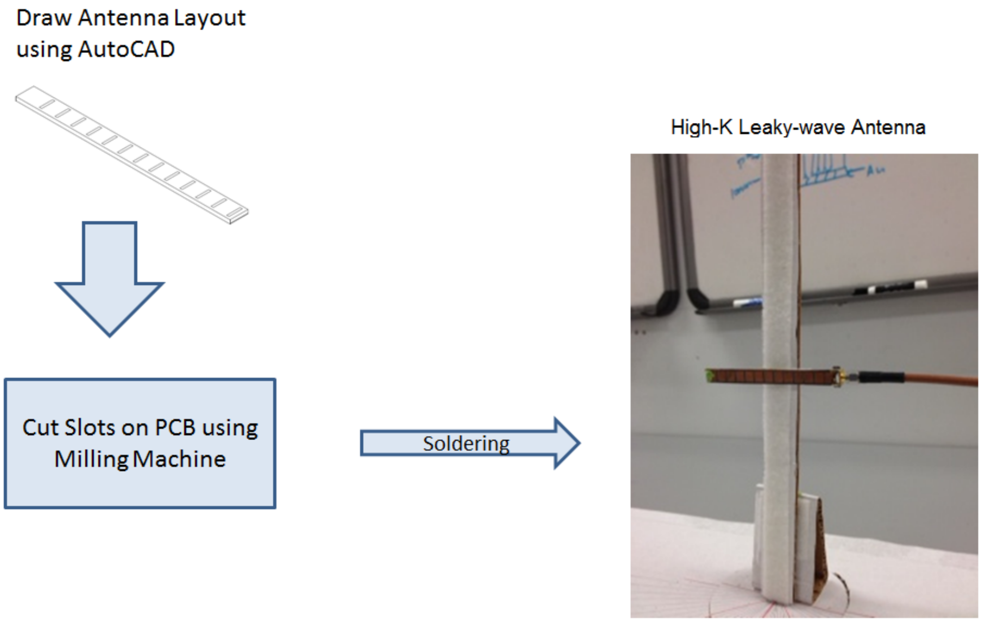


Figure 3.3: Design Flow

3.2 Demonstration

The testbed setup is illustrated in Figure 3.4, which consists of Agilent N9310A RF Signal Generator (9 kHz - 3 GHz), Agilent N9320B RF Spectrum Analyzer (9 kHz to 3 GHz), horn antenna, and leaky-wave antenna. Agilent signal generator is used to generate a RF signal, and its RF output is connected to the designed leaky-wave antenna. Agilent spectrum analyzer with the horn antenna receives the RF signal and measures its power on a circle centered at the point where leaky-wave antenna stands with $52cm$ radius. Figure 3.5 shows the self-made horn antenna. Figure 3.6 shows the moving path of receive horn antenna.

In this demonstration, we will tune the RF frequency from 2.4 GHz up to 2.7 GHz with 500 MHz step size. Aa long as a frequency is given, the RF signal will leak through the slots of the leaky-wave antenna. To observe the main beam direction being changed due to the tuned frequency, the receive horn antenna will measure the signal power from $-70°$ up to $90°$ with $10°$ step size.

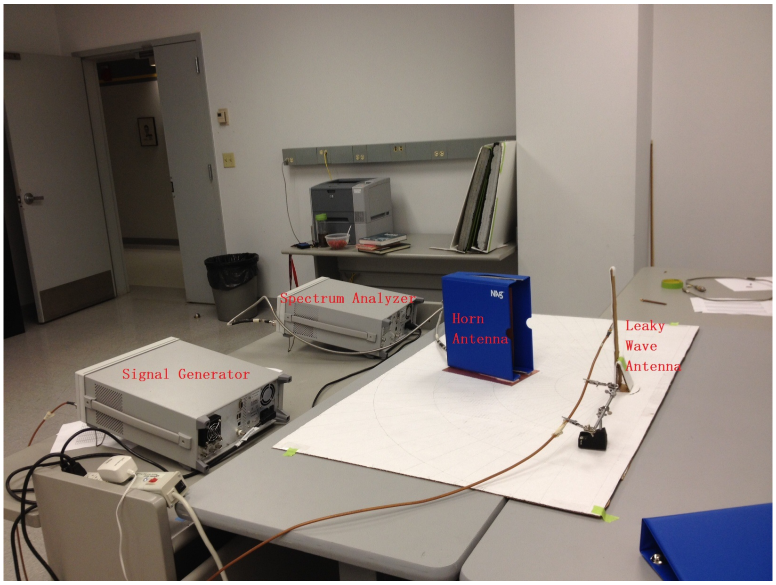


Figure 3.4: Testbed Setup

Figure 3.5: Receiver Horn Antenna

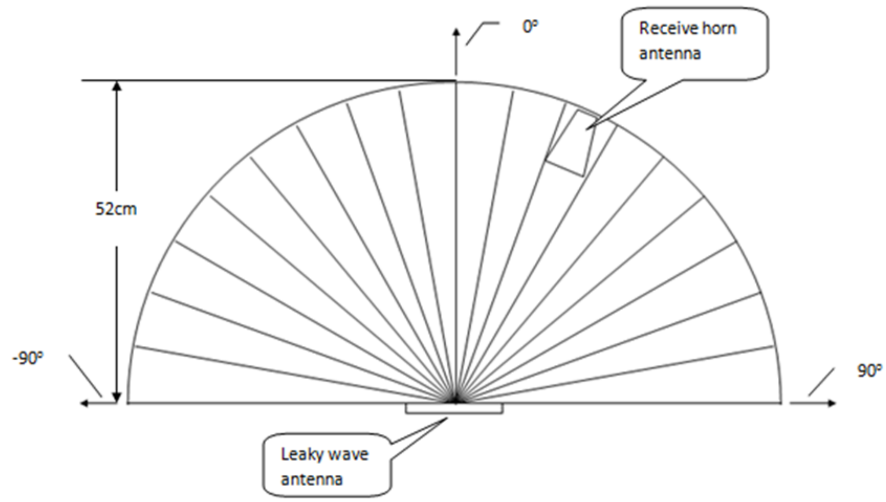


Figure 3.6: Moving Path of Horn Antenna

3.2.1 Case1: RF Frequency Tuned to 2.4 GHz

We first tune the center frequency of signal generator at 2.4 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.1. The figure in Table 3.1 illustrates the main beam direction when $f_c = 2.4GHz$, where the main beam direction is measured at $-32°$.

3.2.2 Case2: RF Frequency Tuned to 2.45 GHz

We increase the center frequency by 500 MHz to 2.45 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.2. The figure in Table 3.2 illustrates the main beam direction when $f_c = 2.45GHz$, where the main beam direction is measured at $-25°$.

Angles (°)	Received Power (dB)	Main Beam Plot
-70	-58	
-60	-53	
-50	-52	
-40	-48	
-30	-47	
-20	-54	
-10	-58	
0	-66	
10	-62	
20	-63	
30	-62	
40	-63	
50	-64	
60	-68	
70	-66	
80	-63	
90	-66	

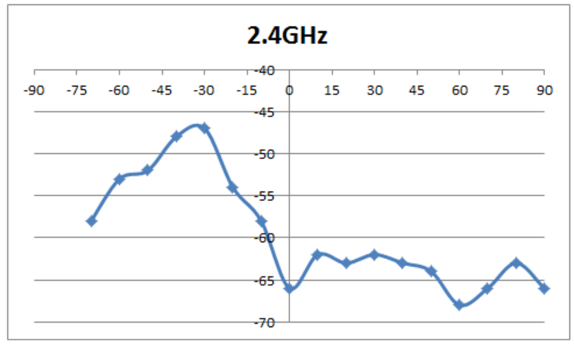


Table 3.1: Received Power and Main Beam Direction When RF is Centered at 2.4 GHz

Angles (°)	Received Power (dB)	Main Beam Plot
-70	-53	
-60	-58	
-50	-56	
-40	-49	
-30	-45	
-20	-43	
-10	-56	
0	-64	
10	-66	
20	-63	
30	-62	
40	-65	
50	-60	
60	-65	
70	-64	
80	-60	
90	-67	

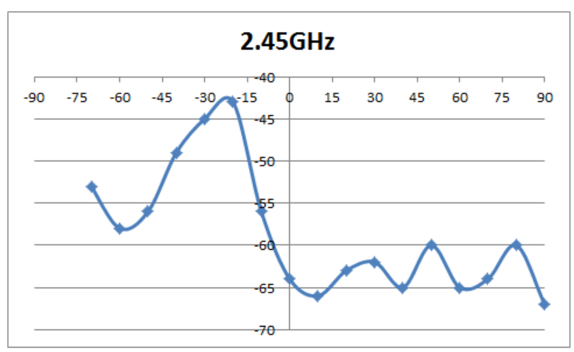


Table 3.2: Received Power and Main Beam Direction When RF is Centered at 2.45 GHz

Angles (°)	Received Power (dB)	Main Beam Plot
-70	-58	
-60	-57	
-50	-55	
-40	-60	
-30	-59	
-20	-47	
-10	-47	
0	-60	
10	-56	
20	-63	
30	-59	
40	-63	
50	-59	
60	-56	
70	-61	
80	-62	
90	-59	

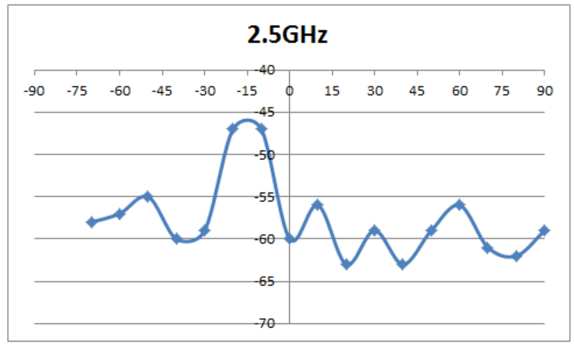


Table 3.3: Received Power and Main Beam Direction When RF is Centered at 2.5 GHz

3.2.3 Case3: RF Frequency Tuned to 2.5 GHz

We keep increasing the center frequency by 500 MHz to 2.5 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.3. The figure in Table 3.3 illustrates the main beam direction when $f_c = 2.5GHz$, where the main beam direction is measured at $-15°$.

3.2.4 Case4: RF Frequency Tuned to 2.55 GHz

We keep increasing the center frequency by 500 MHz to 2.55 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.4. The figure in Table 3.4 illustrates the main beam direction when $f_c = 2.55GHz$, where the main beam direction is measured at $-10°$.

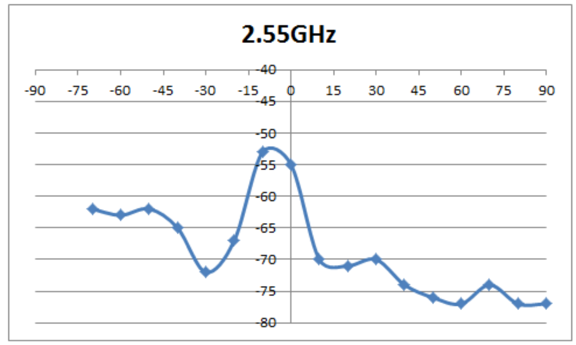
Angles (°)	Received Power (dB)	Main Beam Plot
-70	-62	
-60	-63	
-50	-62	
-40	-65	
-30	-72	
-20	-67	
-10	-53	
0	-55	
10	-70	
20	-71	
30	-70	
40	-74	
50	-76	
60	-77	
70	-74	
80	-77	
90	-77	

Table 3.4: Received Power and Main Beam Direction When RF is Centered at 2.55 GHz

3.2.5 Case5: RF Frequency Tuned to 2.6 GHz

We keep increasing the center frequency by 500 MHz to 2.6 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.5. The figure in Table 3.5 illustrates the main beam direction when $f_c = 2.6GHz$, where the main beam direction is measured at $12°$.

3.2.6 Case6: RF Frequency Tuned to 2.65 GHz

We keep increasing the center frequency by 500 MHz to 2.65 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.6. The figure in Table 3.6 illustrates the main beam direction when $f_c = 2.65GHz$, where the main beam direction is measured at $33°$.

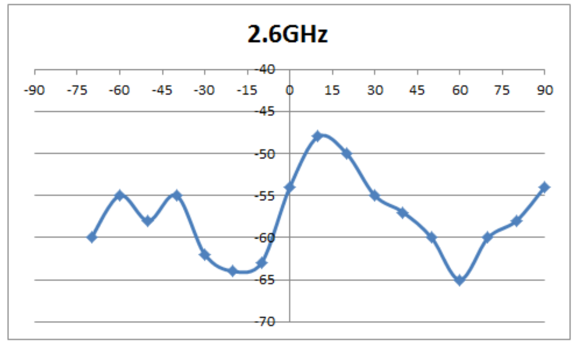
Angles (°)	Received Power (dB)	Main Beam Plot
-70	-60	
-60	-55	
-50	-58	
-40	-55	
-30	-62	
-20	-64	
-10	-63	
0	-54	
10	-48	
20	-50	
30	-55	
40	-57	
50	-60	
60	-65	
70	-60	
80	-58	
90	-54	

Table 3.5: Received Power and Main Beam Direction When RF is Centered at 2.6 GHz

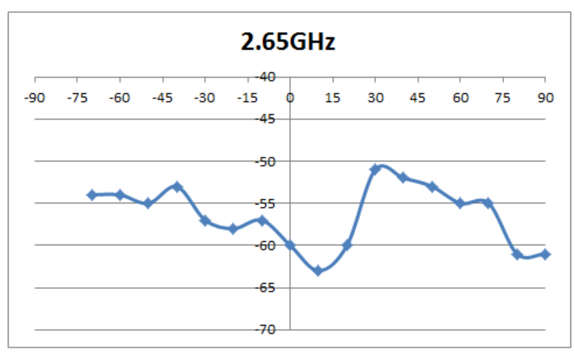
Angles (°)	Received Power (dB)	Main Beam Plot
-70	-54	
-60	-54	
-50	-55	
-40	-53	
-30	-57	
-20	-58	
-10	-57	
0	-60	
10	-63	
20	-60	
30	-51	
40	-52	
50	-53	
60	-55	
70	-55	
80	-61	
90	-61	

Table 3.6: Received Power and Main Beam Direction When RF is Centered at 2.65 GHz

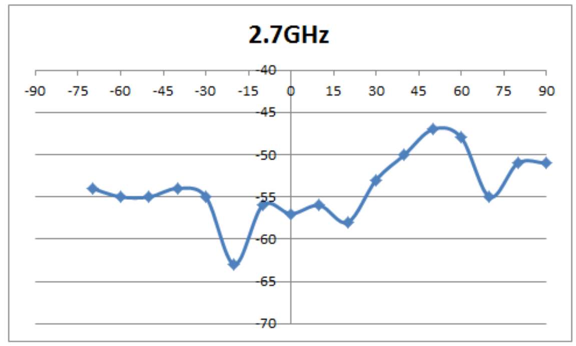
Angles (°)	Received Power (dB)	Main Beam Plot
-70	-54	
-60	-55	
-50	-55	
-40	-54	
-30	-55	
-20	-63	
-10	-56	
0	-57	
10	-56	
20	-58	
30	-53	
40	-50	
50	-47	
60	-48	
70	-55	
80	-51	
90	-51	

Table 3.7: Received Power and Main Beam Direction When RF is Centered at 2.7 GHz

3.2.7 Case7: RF Frequency Tuned to 2.7 GHz

We keep increasing the center frequency by 500 MHz to 2.7 GHz. The horn antenna connected with Agilent spectrum analyzer is moved on the circle which is centered at the leaky-wave antenna with 52 cm radius. The received signal power is listed in Table 3.7. The figure in Table3.7 illustrates the main beam direction when $f_c = 2.7GHz$, where the main beam direction is measured at $50°$.

3.2.8 Comparison between Simulation and Demonstration

Based on the measurement, we can easily observe that the main beam direction is continuously changed when the RF center frequency is tuned from 2.4 GHz to 2.7 GHz. The comparison of the main beam direction between simulation and measurement is summarized in Table 3.8 and Figure 3.7. By tuning the frequency from 2.4 GHz to 2.7 GHz, the main beam direction can be fast swept from $-32°$ to

Frequency (GHz)	MB Direction (°) Simulation	MB Direction (°) Measurment
2.4	-28.14	-32
2.45	-23.24	-25
2.5	-18.35	-15
2.55	-15	-10
2.6	-3	12
2.65	30	33
2.7	42.83	50

Table 3.8: Main Beam Direction Comparison between Simulation and Measurement

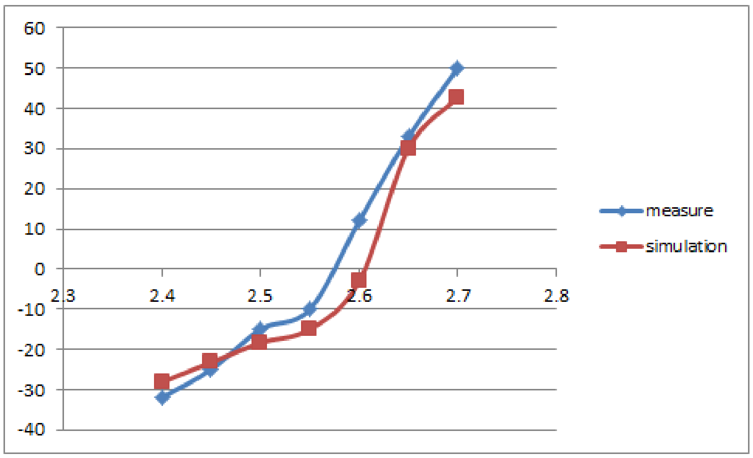


Figure 3.7: Main Beam Direction Comparison between Simulation and Measurement

50°; and 70 degree scanning angles can be achieved continuously. It also matches the simulation results. Our design is further validated by the experiment.

Conclusion and Future Work

4.1 Conclusion

In this thesis, a portable and powerful leaky-wave antenna is designed, implemented, and demonstrated. By applying a high dielectric constant material onto the guiding structure, a low-cost, small size, light weight, and high sensitivity leaky-wave antenna is produced. The designed antenna can reach large scan angles with small frequency tuned. The unique features of the designed leaky-wave antenna are: (1) it is a light-weight, small-size, and portable antenna; (2) by slightly varying the operating frequency from 2.4 GHz to 2.7 GHz, 70 degree scanning angles can be achieved continuously; (3) it is an agile antenna; with 500 MHz operating frequency tuned, the direction of the beam can be easily changed; (4) it could be used as a low-cost phase array antenna.

4.2 Future Work

The current testbed could be optimized in the future. By using signal generator with higher frequency range, the wavelength could be shorter so that the size of the antenna could be optimized. On the other hand, with higher operating frequency, the beamwidth will be narrower so that the radiation power will be large and the gain of the antenna will be increased.

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